

# Approaches to lowering the cost of large space telescopes

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## ABSTRACT

New development approaches, including launch vehicles and advances in sensors, computing, and software, have lowered the cost of entry into space, and have enabled a revolution in low-cost, high-risk Small Satellite (SmallSat) missions. To bring about a similar transformation in larger space telescopes, it is necessary to reconsider the full paradigm of space observatories. Here we will review the history of space telescope development and cost drivers, and describe an example conceptual design for a low cost 6.5 m optical telescope to enable new science when operated in space at room temperature. It uses a monolithic primary mirror of borosilicate glass, drawing on lessons and tools from decades of experience with ground-based observatories and instruments, as well as flagship space missions. It takes advantage, as do large launch vehicles, of increased computing power and space-worthy commercial electronics in low-cost active predictive control systems to maintain stability. We will describe an approach that incorporates science and trade study results that address driving requirements such as integration and testing costs, reliability, spacecraft jitter, and wavefront stability in this new risk-tolerant “LargeSat” context.

**Keywords:** Space telescopes, CubeSats,LargeSats

## 1. INTRODUCTION

Spectacular astrophysical results have been produced by large space missions, such as the Hubble Space Telescope (HST) and the *JWST* (*JWST*), that grew out of small pathfinder missions.<sup>1–3</sup> At present, development risk in astrophysics is largely concentrated on small, low-cost suborbital or Small Satellite (SmallSat) programs, and “a too-big-to-fail mentality pervades agency thinking when it comes to NASA’s larger and most important missions.” [4, Mr. Paul Martin, Inspector General, NASA].

This discrepancy mirrors the launch vehicle landscape before the recent precipitous decline in launch vehicle costs. Elvis, Lawrence, and Seager (2023)<sup>9</sup> recently described how the combination of decreased launch costs,

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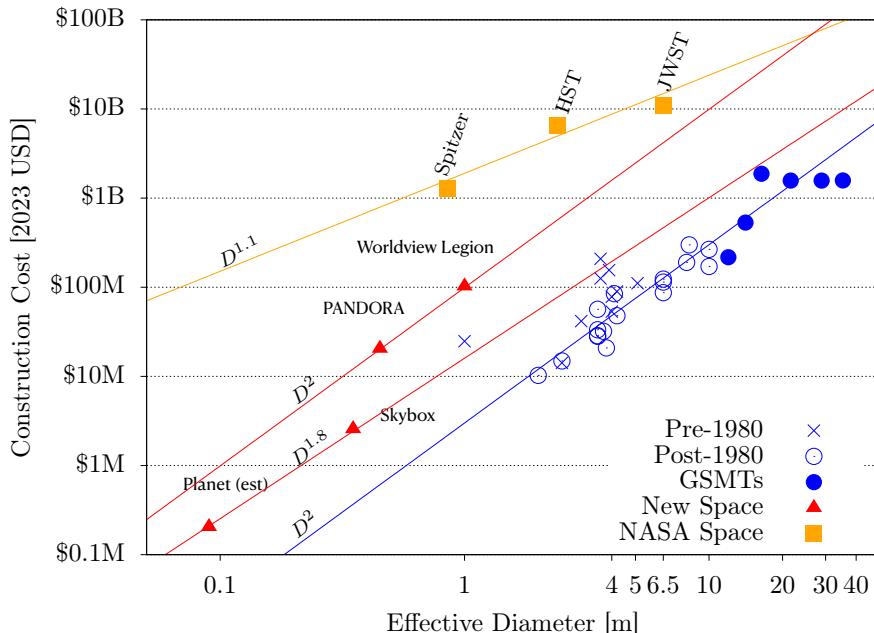


Figure 1. Telescope costs, estimated from public sources, as a function of primary mirror diameter. Ground based observatories are fit with the bottom trend line, blue, and have a significant decrease after 1980 when segmented and honeycomb mirror technologies were introduced (circles). Three classes of space observatories are shown, the bottom  $D^{1.8}$  trend-line shows production line NewSpace SmallSats (for downlooking imaging) while the 3rd line shows limited production NewSpace both for research<sup>5</sup> and imaging. All these costs are small compared to the NASA flagship costs (squares), which are likely flatter due to greater baseline costs. Ground-based telescope costs from Van Belle and Meinel<sup>6</sup> and online sources<sup>§</sup>, space telescopes costs<sup>7,8 ¶||</sup>.

and increased lift mass and volume enabled by the SpaceX Starship has the potential to transform astrophysics mission design.

While it is unlikely that space-borne observatories will fall below the cost of ground-based observatories, Fig. 1 shows that telescope research into honeycomb<sup>10</sup> and segmented aperture telescopes<sup>11</sup> shifted the ground-based cost-curve down by over a factor of two after  $\sim 1980$ , and NewSpace<sup>12</sup> economies of scale have recently enabled very low-cost, albeit small, imaging missions. Thus, research and new economies of scale enabled by prior research into optics, commercial electronics, and the SpaceX StarShip could have a similar impact on space astronomy and drive the cost of multiple large observatories down into the regime between the NewSpace projections and ground-based observatories. This study is inspired by pathfinding work over the past several decades on space telescope design and cost-efficient academic, government, and commercial SmallSat and CubeSat missions. A small portion of that work is described below; which combined with technological advances (Sec 2) and a culture of openness (Sec. 4.1) is beginning to merge with recent experience in SmallSat development in academia. This merger is enabling University-led large space missions, potentially bringing down cost and increasing dissemination of research by integrating engineering and science teams. An examples of such integration is the OSIRIS-REx Camera Suite (OCAMS) – an instrument which sucessfully imaged the asteroid Bennu after a deep space flight. The OCAMS team in the UA Lunar and Planetary Laboratory worked with Steward Observatory for systems engineering and mechanical support and the College of Optical Sciences for the optical train, with inputs from Utah State University Space Dynamics Lab and others.<sup>13</sup> Similarly, the Aspera SmallSat mission<sup>14</sup> science payload is being built by a university collaboration led the University of Arizona and the spacecraft is being built by the University of Toronto. This manuscript will provide a brief introduction to past studies of relevant large space telescope designs, establishing the field as an academic research area, and then describe a mission concept currently being studied by a team from several US universities.

<sup>¶</sup>[https://elt.eso.org/about/faq/#question\\_9](https://elt.eso.org/about/faq/#question_9)

<sup>||</sup>[https://www.jpl.nasa.gov/news/press\\_kits/spitzer/quick-facts/](https://www.jpl.nasa.gov/news/press_kits/spitzer/quick-facts/)

<sup>§</sup><https://www.planetary.org/articles/cost-of-the-jwst>

## 1.1 History of Astronomical Space Telescope Research

Design, simulation, and qualification of optical systems for launch requires a process of research into materials, mechanical, thermal, controls, and structural engineering.

Nancy Grace Roman, Lyman Spitzer, and Aden Meinel were among the early visionaries who saw in the first decade of the space age the great potential for space observatories. Spitzer<sup>15,16</sup> established the basic physical parameters of a large space observatory and its astrophysical motivation. Roman<sup>1,17</sup> developed an observatory operational concept around guest observers with near real-time control and a rotating suite of instruments, inspired by the Kitt Peak National Observatory (KPNO). There were many learning experiences from early missions, such as the Orbiting Astronomical Observatories (OAO)<sup>17-19</sup> launched between 1966-1972 with instruments developed at University of Wisconsin-Madison and Princeton, Infrared Astronomical Satellite (IRAS)<sup>20</sup> launched in 1983, International Ultraviolet Explorer (IUE)<sup>21</sup> launched in 1978 and HST, advancing technologies and concepts of operation for future flagship astronomical observatories larger than 1 m became an established area of applied research at universities across the US and world.

Research into the launch worthiness of large space observatories dates back to the beginning of the space age. In 1962, Meinel described “high resolution optical telescopes” including the OAO 0.9m telescope<sup>22</sup> and succinctly described the challenge of building a simple system that survives launch: “During the launch into orbit a telescope may be subjected to vibration of approximately 5 to 10 g’s over a frequency range of 5 to 1500 cycles per second. As a consequence, either the engineer must find a design that will preserve optical collimation or the astronomer will have to realign his optical systems after the telescope arrives in orbit.”<sup>23</sup> In the 1980s, at the University of Arizona (UA) the Space Infrared Telescope Facility (SIRTF, now known as Spitzer) team studied different approaches to calculating the stresses on the 1 m telescope mirror and published details of the design, finite element method (FEM) approach, and compared methods for calculating the probability of launch survival for different support designs.<sup>24</sup> In the early 2000s, also at UA, part of Next-Generation Space Telescope (NGST) technology development<sup>25-27</sup> 0.5 m and 2.0 m lightweight active mirrors were built and tested including acoustic tests of prototypes.

Detailed FEM of the vibro-acoustic survival of active 1-m class space telescope segments have been studied at MIT.<sup>28</sup> Similarly, the response of JWST mirror segments to launch level acoustics and vibrations was modeled, tested and published.<sup>29</sup> The European Space Agency (ESA)’s large aperture telescope technology (LATT) project<sup>30</sup> built a 0.4 m active telescope optic for space and qualified it for space to technology readiness level (TRL)-5 via measurement of its response to launch loads. Overall, FEM approaches have improved our confidence that optical designs will survive launch, prior to test.

Control of large space structures, particularly line-of-sight pointing, is another key area of research advanced by US universities to enable large space observatories. For example, researchers at Texas A&M University have built and published a detailed reaction wheel model to improve pointing control of large spacecraft.<sup>31</sup> Similarly, an MIT-led series of experiments summarized by Saenz-Otero (2005)<sup>32</sup> include the Middeck 0-Gravity Dynamics Experiment<sup>33</sup> and Middeck Active Control Experiment (MACE),<sup>34</sup> which tested dynamics and control of large structures required to control the attitude of large space observatories in flight aboard the Space Shuttle.

Thermal stability of large space telescopes is an essential technology for space astronomy, enabling long-duration exposures on faint objects without changes in the image quality or the distribution of starlight. Examples include the 1.5-m AMTD-2 mirror, which was studied theoretically<sup>35</sup> and then qualified at picometer level stability in a vacuum cryo-shroud simulating space.<sup>36</sup>

Material selection is a key aspect of telescope design and many candidate materials are typically studied before the optimal observatory design for a particular astrophysical question to be established. JWST went through an extensive study of options<sup>37</sup> and published details of the cryo-vacuum testing.<sup>38</sup> The JWST primary mirror segments are Beryllium but several other materials were considered and studied in active research programs, including ultra-low expansion (ULE) glass at Kodak<sup>39</sup> and Zerodur<sup>25</sup> at the University of Arizona. The Kodak AMSD mirror program studying ULE options, including wavefront error in cryogenic vacuum, were published.<sup>39</sup> The 3.5 m SiC Hershel telescope was cryogenically tested and discrepancies between the FEM and the physical performance of the system were identified, studied, and published.<sup>40</sup>

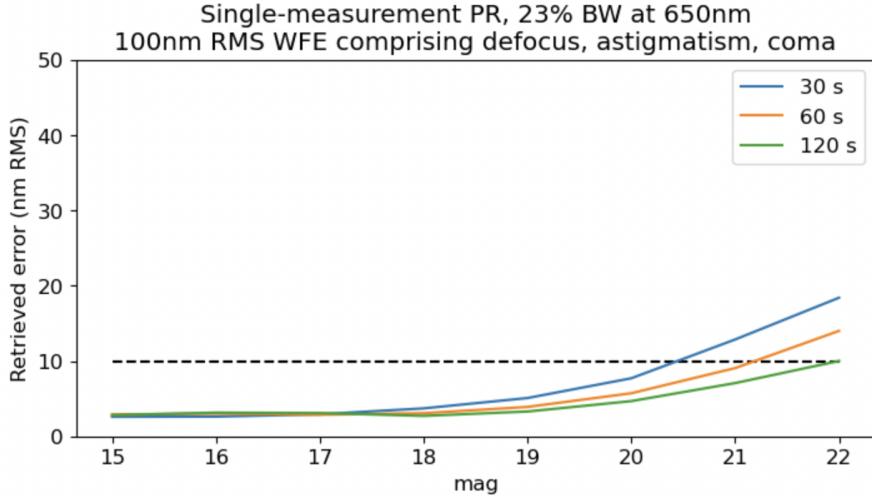


Figure 2. Single-star phase retrieval wavefront error versus stellar magnitude for a modern CMOS sensor (e.g. IMX571 or IMX455 operating at  $\sim 1^\circ$  Celsius).

West et al. 2010<sup>41</sup> combined some of these development areas and studied the launch survival of 4 m borosilicate primary mirrors and introduced the concepts of thermal figuring for honeycomb borosilicate space mirrors and the use of off-axis stars for guiding and wavefront sensing. This design was recently cited in the conceptual design of a 20 m space telescope<sup>42</sup> on the Moon. A similar 50-100 m concept is under study at Paris Observatory<sup>43</sup> and these concepts prove key to the simpler, 6.5m space telescope concept discussed below.

Closely related to thermal control and observatory design is wavefront sensing and control techniques to maintain the alignment and prescription of optical surfaces and thereby preserve image quality. A range of scientific studies have investigated optimal wavefront sensing and control approaches for large space telescopes, including ultra-stable 6 m telescopes with active primary mirrors,<sup>44</sup> 9.2 m space telescopes with formation-flying laser guide stars,<sup>45–47</sup> and active space telescopes with predictive thermal modeling.<sup>48</sup> There have been several research missions to test approaches to wavefront control and the TRL of these approaches for future missions. The PICTURE sounding rocket flights in 2011 and 2015 demonstrated piezo-electric fine pointing and power-on of a microelectromechanical systems (MEMS) deformable mirror in space<sup>49,50</sup> and the Deformable Mirror Demonstration Mission CubeSat<sup>51,52</sup> launched in 2020 was a prototype space-Adaptive Optics (AO) system that performed closed-loop wavefront control using a MEMS mirror.<sup>53</sup> The methods for simulation of large optical system performance, with and without wavefront control, are another active research area that has been significantly advanced by JWST and the Roman Coronagraph<sup>54–60</sup> including through testing<sup>61,62</sup> and on-orbit performance.<sup>63</sup> These parallel efforts to bring precision wavefront sensing and control to both small and flagship missions have left us with a wide-range set of tools to maintain telescope optical performance in space. The next section will detail several industrial developments that can be leveraged to increase the efficiency of space observatory development.

## 2. ENABLING TECHNOLOGIES

### 2.1 Launch Cost and Payload Volume

Spacecraft launch costs and their impact on design are difficult to quantify from public data, but a recent analysis by CSIS<sup>64</sup> suggests a  $> 40\times$  decrease in heavy lift launch costs between the Shuttle era and the SpaceX Falcon Heavy; however, the gain decreases to  $\sim 3\times$  for the ratio between the Saturn V and Falcon Heavy.

The fairing of the SpaceX Starship has the potential for a 6.5 m JWST-class telescope to be directly launched with a monolithic mirror, removing the cost and complexity of segmented mirror designs. Additionally, while the relative cost of Starship is undetermined, costs as low as \$10/kg and prices as low as  $\sim 100/\text{kg}$  to LEO have been widely reported, a  $>> 10\times$  decrease versus Falcon Heavy.<sup>64–66</sup>

## 2.2 Sensor Technology

The steady advance of silicon sensor technology, driven by economies of scale, with billions of devices manufactured per year,<sup>67</sup> has reduced sensor noise and increased pixel count significantly over the past several decades. For example, the Hubble  $1024 \times 1024$  Space Telescope Imaging Spectrograph (STIS) charge-coupled device (CCD) read noise is  $4.4 - 7.8 \text{ e}^- \text{ pix}^{-1}$  and dark signal is  $0.003 \text{ e}^- \text{ sec}^{-1} \text{ pix}^{-1}$  at  $-86^\circ$  Celsius, whereas a modern commercial off-the-shelf (COTS) complementary metal–oxide–semiconductor (CMOS) sensor has  $1 - 3.4 \text{ e}^- \text{ pix}^{-1}$  and reaches the same dark signal per pixel at  $0^\circ$ Celsius with as many as 150 megapixels.<sup>68</sup> While CMOS pixel sizes continue to decrease, modern silicon processing advances can be expected to continue to reduce dark current per unit area to improve overall signal-to-noise. CMOS sensors are inherently more radiation tolerant than CCDs and so are well suited for space missions.<sup>69</sup> Modern CMOS sensors also allow faster frame rates than previous generation of silicon imagers. Finally, these devices are being fabricated with increasing physical areas and at higher yields for effectively lower cost.

## 2.3 Radiation Tolerant Computing

Historically purpose built flight computers ran assembly language and required costly and niche software development skills. Currently however, advances in COTS computing hardware and software, particularly increases in processing power and radiation tolerant computing, has allowed the deployment of widely supported open-source operating systems such Linux in space,<sup>70</sup> decreasing development time while allowing highly complex control systems at relatively low-cost, with recent demonstrations including the operation of the Ingenuity Mars Helicopter<sup>71</sup> and closed-loop jitter and wavefront control on CubeSats running Linux.<sup>53, 72, 73</sup>

## 2.4 High Earth Orbits

The Sun-Earth L2 point has become the destination for space observatories requiring a thermally stable environment, with the price being increased communication power requirements and propulsion  $\Delta V$ . Recently, the TESS mission<sup>74</sup> demonstrated<sup>75</sup> an alternative: a 13.7 day period, high Earth orbit (HEO) in 2:1 resonance with the Moon, reached via lunar gravity assist. The TESS HEO orbit provides a large continuous sky coverage in a thermally stable low radiation environment for relatively low  $\Delta V$ ,<sup>76</sup> lowering the propulsion needs for space observatories and increasing potential data downlink relative to L2 orbits for the same transmitter power.

## 2.5 Large Optic Fabrication and Design Optimization

The cost of manufacturing large optical systems depends heavily on the primary optic material. Honeycomb borosilicate mirrors cast by the Richard F. Caris Mirror Lab (RFCML) at UA at  $1165^\circ \text{ C}$ <sup>77</sup> are relatively affordable to manufacture in large apertures, with a complete 6.5 m ground-based observatory costing of order \$70M USD in 2020 dollars.<sup>78</sup> These mirrors, combined with the anastigmatic three-mirror (TMA) optical design proposed by Korsch,<sup>79</sup> and recently demonstrated on JWST, enable all-reflective large-field-of-view telescopes<sup>80</sup> which can continuously observe a significant number of stars in parallel over a wide range of wavelengths.

## 2.6 Phase Retrieval

When Hubble was launched with polished-in spherical aberration, phase retrieval using starlight to determine the optical wavefront error, which would be corrected by repair missions, became a critical area of research.<sup>81-83</sup> These families of algorithms were later extended for wavefront sensing of the JWST observatory.<sup>61, 63, 84</sup> Phase retrieval allows a wide-field science instrument to operate as the wavefront sensor, extending the concept of using the science instrument for guiding pioneered by TESS and planned for Roman Space Telescope.<sup>85, 86</sup>

## 2.7 Project, Interface, and Document Management

Over the past several decades, advances in development processes for software with version control, project management, test-based design, and continuous integration and deployment have increased the development pace of increasingly complex software.<sup>87</sup> With strategic management, integrated software and hardware teams can cycle through the development process faster.<sup>88</sup> Breaking down the communication and cultural barriers between software and hardware teams in astronomical space instrument development has the potential to create smaller, more agile teams. As shown by experience gained through the Vera C. Rubin Observatory and the Gaia

mission, a project can facilitate better communication is by using machine readable interfaces, specifically for software development and simulation teams, but also for disseminating commonly referenced numbers such as the fundamental parameters describing the optical design. E.g. using the code (or files read in by the code) as the interface control document [89, and references therein] and utilize JSON Schemas\* to define the interface structure and definition. This enables the input parameters themselves to be verified upon population using standard software packages (e.g. [jsonschema in Python](#)) and offers the ability to populate useful metadata available directly with each parameter, eliminating error-prone manual extraction of variables from definition documents. This structure of ICD is especially useful for performance simulations, particularly when evaluating the impact of potential and/or upcoming changes.

Document management has long been a cornerstone of developing reliable aerospace and astronomical instruments.<sup>90</sup> One existing trial of such an approach was the *git* based requirements management used early in the Roman Coronagraph science investigation teams,<sup>91</sup> where systems engineers adopted a software requirements tool (Doorstop<sup>92</sup>) to improve documentation change tracking and automated distribution. The natural next step is tying these broad systems requirements to test plans, linking them in a *git* tracked system, and using a code-review-like process to develop both hardware and software tests. These tools make an iterative, prototype-heavy design process more feasible since lessons learned are captured naturally.

### 3. CONCEPTUAL DESIGN

We seek to bring together the I) well established history of space telescope development, II) the recent NewSpace/SmallSat revolution, and III) recent technological advances in hardware and software, into a point design which can be iterated upon, providing a starting point for concept development and improvement leading to the building of prototype(s) to meet the specific requirements of space astronomy, particularly cosmology and exoplanet direct imaging. The proliferation of CubeSats and SmallSats have shown that in a relaxed design environment with few hard constraints (mass, volume, power), engineering creativity opens. Decreased launch costs and the successes of CubeSats and SmallSats can overwhelm the mission designer with possibilities. To overcome this challenge, we set ourselves the constraints of two challenging toy problems, I) precision spectrophotometry of faint sources such as Type Ia supernovae, and II) high-contrast imaging of sub-Neptune planets around nearby stars. Further constraints to focus the designers' imagination are: III) use of the publicly available fairing of the SpaceX starship launch vehicle<sup>†</sup> and IV) use the field-proven Richard F. Caris Mirror Lab 6.5 m light-weighted borosilicate honeycomb mirror without modification.<sup>93–97</sup>

The sections below will highlight key aspects of a low-cost, large monolithic observatory conceptual design. Sec. 3.1 will introduce the TMA optical design, which is discussed in greater detail by Kim et al.,<sup>98</sup> with the alignment error budget presented by Choi et al.,<sup>99</sup> while Derby et al.<sup>100</sup> describes an integrated modeling of the observatory using continuous a wavefront control approach, which is studied in the lab by Kang et al.<sup>101</sup> and enabled by continuous control of mirror bending modes, which are described by Blomquist et al.<sup>102</sup>

#### 3.1 Active Optical Design

To use a borosilicate mirror on the ground requires active control to minimize thermal and gravitationally-induced wavefront gradients.<sup>77</sup> Similarly in space, thermal gradients and distortions due to the support structure or gravitational release must be corrected via actuators and/or thermal figuring. To design a system that can correct these errors, they must be predicted with sufficient margin prior to launch. Even for a monolithic telescope, on-orbit measurement and correction allows relaxation of model accuracy, thereby lowering the costs of model validation and test campaigns, which are significant drivers of large observatory costs. Lyman Spitzer<sup>15,16</sup> established the basic physical limitations and derived the natural guide star limitations on guiding the attitude of a space observatory. This approach was applied by the HST Fine Guidance Sensor (FGS).<sup>103</sup>

Following the scaling relations described in Hill et al (2013) [77, §1.5.7] we can approximate the thermal requirements for a borosilicate primary mirror. A typical UA mirror figure is  $\sim$ 14 nm RMS surface, 28 nm RMS

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\*<https://json-schema.org/>

<sup>†</sup>[https://www.spacex.com/media/starship\\_users\\_guide\\_v1.pdf](https://www.spacex.com/media/starship_users_guide_v1.pdf)

wavefront error (WFE), after removal of low-order modes.<sup>95</sup> For general astrophysics, to maintain diffraction-limited imaging (see Choi et al.<sup>99</sup>) at  $1\mu\text{m}$  one could allocate  $\sim 30$  nm RMS WFE to thermal distortions and sensing accuracy of  $\simeq 10$  nm. The coefficient of thermal expansion (CTE) ( $\alpha$ ) of Ohara E6 borosilicate at room temperature is  $\alpha = 2.78 \times 10^{-6}/^\circ\text{C}$ . Characteristic lengths of the mirror range from the phase sheet (27 mm), the cell center spacing (192 mm), and the overall thickness  $h = 711$  mm.<sup>94</sup> The last dimension leads to a vertical thermal stability requirement throughout the mirror given by:

$$\delta T = \frac{\text{WFE}}{\alpha h} = \frac{10\text{ nm}}{\alpha h} \quad (1)$$

Fig. 2 shows for a 6.5 m telescope with modern COTS CMOS sensors, a single 22nd magnitude star allows sensing of low order Zernike polynomials to 10 nm WFE in 120 seconds. Assuming a conservative ground-based AO controller bandwidth of  $10\times$  the sampling rate (i.e. 20 min), thermal drifts of  $\sim 0.25\text{ mK/min}$  (or  $\sim 0.5\text{ nm/minute}$ ) can be sensed and controlled with a single 22nd mag star.

To estimate the field-of-view (FOV) required to always have two stars sufficiently bright for monitoring low-order aberrations, we take the dim star counts at the poles from Bahcall,<sup>104</sup> reject the binary fraction ( $\sim 50\%$ ) and find that  $a > 10\text{ arcmin}^2$  wavefront sensor area FOV is required. In order to have margin on sensor failure, Poisson fluctuations in the star counts and enable other science channels to coexist with the incomplete fill-factor of COTS sensor packaging, this was translated into  $a > 50\text{ arcmin}^2$  focal plane, described in detail in Kim et al.<sup>98</sup>

### 3.2 Fault Tolerant Instruments

A 6.5 m telescope in space opens up new scientific paradigms. The photometric stability of a space telescope allows high-precision photometry much beyond that of ground-based observatories. Even low-cost nanosatellites have made contributions to the literature<sup>72,105</sup> and a 6.5 m space observatory with even basic instruments has groundbreaking potential. In this section, we describe instruments that go beyond the basic imaging required for photometry and continuous wavefront control described in the last section and put forth affordable instrument concepts that leverage the space platform to address unanswered questions in cosmology and exoplanet research.

#### 3.2.1 Two-octave spectrograph

A single high-bandwidth, moderate resolution spectrograph with continuous coverage from  $0.4\text{--}1.7\text{ }\mu\text{m}$  allows measurement of a wide range of astrophysical phenomena and is particularly useful for the precision history and rate of the expansion of the universe out to redshift  $z = 2$  and can thereby track the evolution of dark energy through precision spectrophotometry,<sup>106</sup> for instance using the techniques of Boone et al (2021)<sup>107,108</sup> without requiring cross-calibration of multiple instruments. Table 1 describes a set of instrument requirements to accomplish this science using an Integral Field Spectrograph (IFS) instrument much like those found on ground-based telescopes<sup>109–112</sup> or previously proposed for space.<sup>113,114</sup>

Parameter	Value	Notes
Wavelength range	$\lambda = 400\text{ nm to }1700\text{ nm}$	Allows Type Ia supernova (SN) characterization at redshifts $0 < z < 2$
Wavelength resolution	$R=100$ at $1\mu\text{m}$	$S/N > 10$ per resolution element (in the rest-frame B band for a flux of AB=25 mag)
FOV	$\sim 1\text{ arcsecond}$	Allows spectrophotometry, including subtraction of host galaxy from SN spectra
Photometric accuracy	3 millimag	Relative to standard stars

Table 1. Desired Spectrograph Instrument Parameters.

Parameter	Value	Notes
Clear Entrance Aperture	2m-2.5 m and 0.6m-1 m	independent sub-apertures
Design life	1+ year (3+ goal)	sets radiation sensitivity
Primary operation wavelength	650 nm	
Nominal filter bandwidth	2%	minimizes sensitivity to WFE
Deformable Mirror Actuator Count	952	BMC Kilo-C DM 1.5um
Deformable Mirror Actuator Stroke (max)	1500 nm	BMC Kilo-C surface stroke for 4x4 actuators
Coronagraph mask	Charge-6 VVC	
IWA	$2.4\lambda/D$	depends on mask
OWA	$10\lambda/D-15\lambda/D$	depends on WFE
Sensitivity	1e-8 or dimmer star-planet flux ratio	sensitivity to debris disks and sub-Neptune size planets in habitable zones of nearby stars

Table 2. Desired ESC Coronagraphic Instrument Parameters.

### 3.2.2 Extra-solar camera

The baseline parameters of a simple coronagraph or ExtraSolar Camera (ESC) design (Table 2) are designed around unobstructed sub-apertures to simplify coronagraph design and construction, maximizing science per dollar. The straightforward single Deformable Mirror (DM) instrument layouts are inspired by the CDEEP/SCoOB and PICTURE-C designs.<sup>115-118</sup> ESC concept is built around survey bright stars for reflected light from planets and the stellar flux enables sensing of the telescope WFE much more precisely than in the general astrophysics example above, enabling control down to the sub-nanometer regime required to reach  $10^{-8}$  contrasts with a simple charge-6 vector vortex coronagraph and continuous dark hole wavefront sensing, a concept described in more detail in Derby et al.<sup>100</sup>

### 3.3 Parameterized disturbances

Integrated Structural-Thermal-Optical-Performance (STOP) analysis is becoming the standard for both large<sup>119,120</sup> and small space-telescopes.<sup>121</sup> These models unfortunately are often time-consuming to build and run, leading to the dilemma of whether to design the active optics system before or after the observatory design is complete and STOP modeling of input disturbances is complete. To ease this causality dilemma, we adopt a parametric approach inspired by ground-based AO<sup>122</sup> using power spectral density (PSDs) early in the design process to approximate realistic disturbance and create requirements envelopes.<sup>46</sup> Past work on high-contrast imaging has estimated leakage with spatio-temporal PSDs.<sup>123</sup> As a quick first-approximation, we generate a 2D data cube with parameterized PSD and express the simplified von Karman PSD as:

$$PSD(f) = \frac{\beta}{(1 + f/f_n)^\alpha}, \quad (2)$$

where  $f_n$  is the so-called “knee frequency” of the distribution,  $\alpha$  is the fall off power-law and  $\beta$  is a normalizing scalar. Fig. 3 shows the measured PSD for an example realization of this data cube for the first 25 Zernike polynomials. Initial results of using this model to exercise an end-to-end observatory control system or “digital-twin” is described in this proceedings by Derby et al.<sup>100</sup> To generate a synthetic time series, each time-evolving term is assumed to start at zero and then a 40 hr. time series is generated randomly. This results in a conservative example, since in a physical system error Zernike terms are correlated with each other and with temperature – an opportunity for optimized predictive controllers.<sup>36,124,125</sup> For the example plotted, the maximum gradient in focus is  $\sim 1$  nm/minute, or approximately the value we expect to be able to control (see Sec. 3.1). This example only addresses one example PSD; future publications will establish the bounding cases of observatory control as a function of  $F_n$ ,  $\alpha$ , and  $\beta$ .

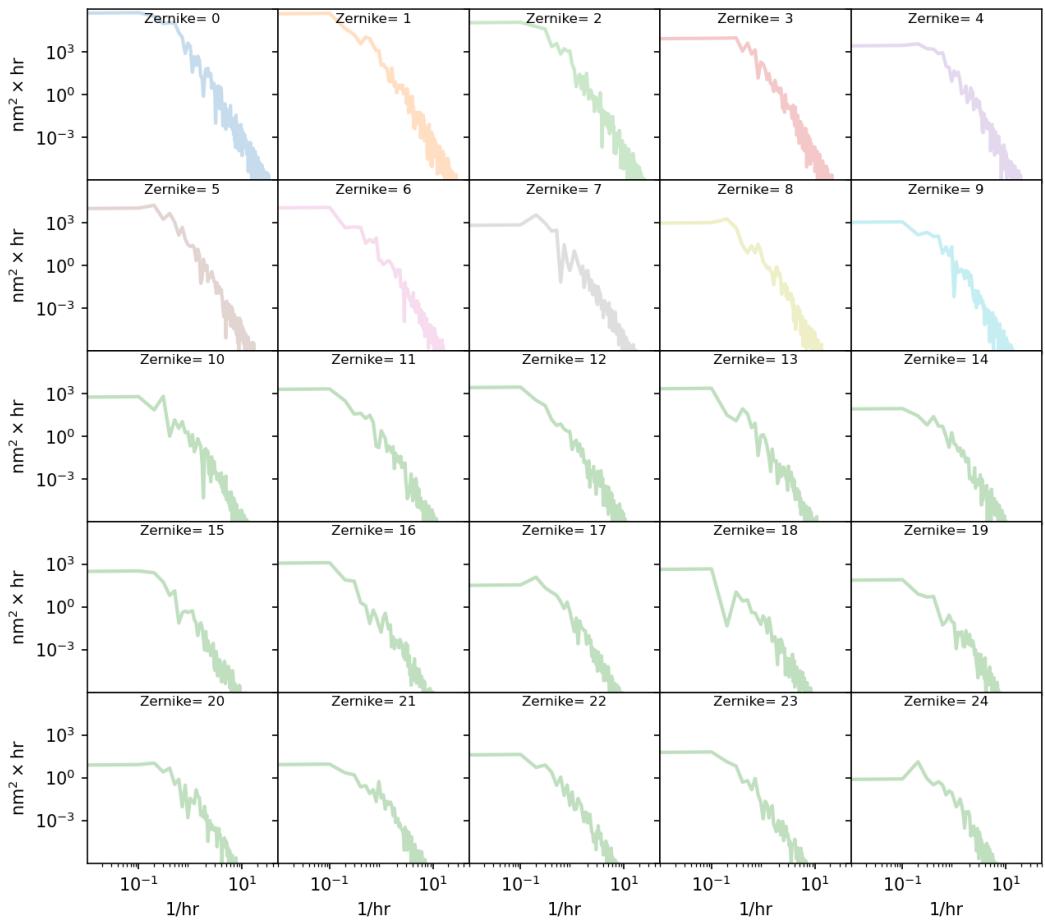
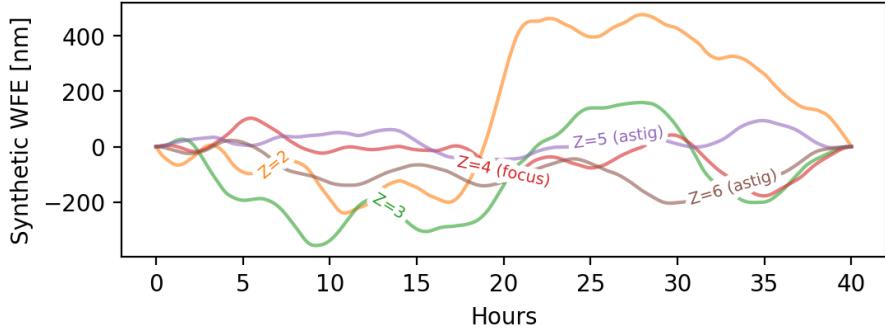


Figure 3. Example realization of statistically generated spatio-temporal wavefront evolution. The top panel shows the time evolution of the amplitudes of the first few wavefront error Zernike terms, which are multiplied by Zernike coefficients to generate a 2D synthetic STOP analysis output. The bottom grid shows the PSDs measured from time-series wavefront error amplitude functions. For these toy models, the temporal PSD has a knee at 0.45/hour and  $\alpha = 7$ ; for the spatial PSD  $f_n=5/Zernike\ number$  and  $\alpha = 6$ , the spatial PSD falls off quickly since Seidel aberrations dominate thermal misalignment and the temporal PSD is expected to be dominated by slow thermal effects. To tolerance a system many such realizations, with different values of  $\beta, \alpha$ , and  $f_n$  will be explored.

### 3.4 Software

As much as possible, it is desirable to use “off-the-shelf” parts that have previously been space-qualified in some manner, along with designs and flight software that have been used in space or deployed to professional observatories. This enables significant code reuse. In particular, the real-time wavefront and control software inherited from the MagAO-X instrument,<sup>126</sup> in turned inherited from the Subaru Extreme AO system,<sup>127</sup> is being tested on two adaptive optics testbeds at the University of Arizona Center for Astronomical Adaptive Optics.<sup>118,128</sup> Ground-based observatories have long relied on the INDI (Instrument-Neutral Distributed Interface) protocol and re-using this codebase is an appealing way to lower the cost of deploying a large space observatory. Unfortunately, hardware and software faults in devices can crash INDI servers, thus the process management for MagAO-X and CAAO testbeds was recently upgraded to include a *resurrector* function, which monitors for stale processes via a hexadecimal heartbeat (“hexbeat”) representation of a time at some point in the future. If the current time exceeds the hexbeat the process is terminated and restarted. This code has been tested and is available publicly via the MagAO-X project<sup>‡</sup>.

## 4. MANAGING RISKS

### 4.1 Reliability

Reliability comes from failure. Automotive manufacturers each build thousands of prototypes per year<sup>129</sup> and test them on the road to discover design weaknesses. Space missions, especially CubeSats, have a notoriously low mission success rate, < 30% for full mission success and < 70% for partial mission success, even for traditional-space companies. But the success rate increases significantly once a team has launched several missions.<sup>130</sup> It appears that building a complete prototype and testing it in-flight informs both the design and the engineering team’s knowledge base. A similar pattern is evident in launch vehicles, with the Space Exploration Technologies (SpaceX) Falcon 1 first succeeding on its 4th attempt.<sup>131</sup> *Thus, a commitment to multiple flights is an essential part of developing a new platform or paradigm.*

Organizations vary in their ability to learn from external failures and to continue innovating despite lessons learned. Academic and government NewSpace has benefited greatly from both organic and coordinated approaches to communicating lessons learned; for example the NASA Small Satellite Systems Virtual Institute (S3VI) and its federated search tools,<sup>132</sup> and the JPL F’ (F Prime) Flight Software System.<sup>133</sup>

Adapting SmallSat concepts to enable larger satellites at lower costs will require several ingredients:

1. Teams with deep knowledge of lessons already learned in both SmallSat and traditional space sectors.
2. Commitment to multiple flights to build institutional knowledge.
3. Commitment to open communication and documentation.

The pace of the SmallSat revolution has been accelerated by openness, and while not a prerequisite for a given mission, open sharing of lessons through fora such as the CalPoly CubeSat Developers Workshop, the Utah State Small Satellite Conference as well as direct sharing of designs and source code through online repositories has enabled a burgeoning field – as of 2023 there are over 138 NASA SmallSat science missions flown or in formulation.<sup>134</sup>

### 4.2 Launch environment

Given the large uncertainties in the expected SpaceX Starship launch environment, only preliminary enveloping studies are possible. However, UA honeycomb borosilicate mirrors (Fig. 4) designed for the ground have several promising characteristics that suggest launch is feasible; a detailed analysis is beyond the scope of this manuscript and will be presented at a later date.

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<sup>‡</sup><https://github.com/magao-x/MagAOX/blob/resurrector/apps/resurrector/README.md>

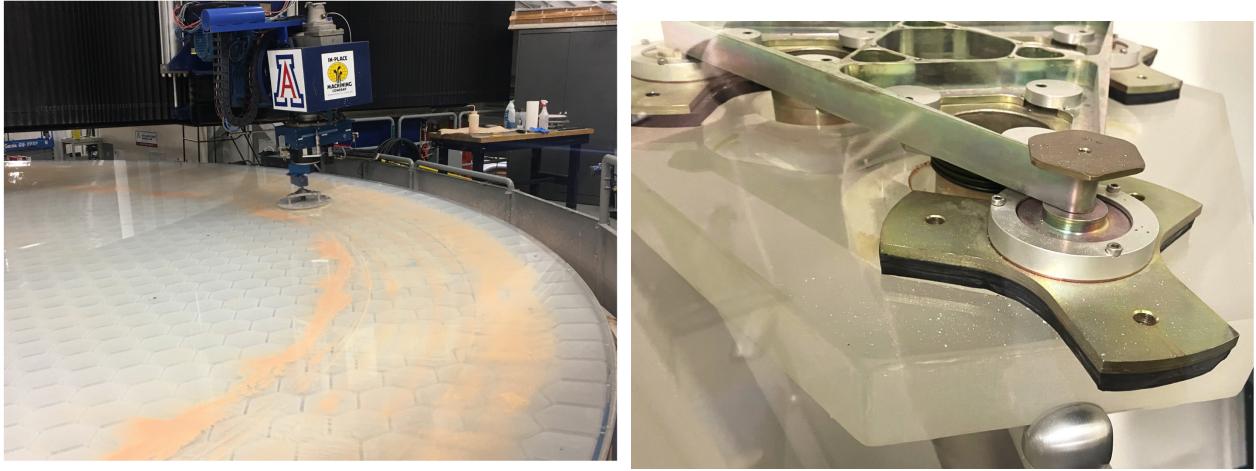


Figure 4. Left: GMT segment 3 being polished, reproduced from Martin et al.<sup>135</sup> Right: Typical UA Mirror Lab load spreader mounted to a cross-section of a typical borosilicate mirror polished backside. From bottom to top: the approximate inch- thick backside, RTV bond, mounting puck, and triangular load spreader. These designs are described in detail in past papers.<sup>135-139</sup> The thick RTV layer is expected to provide significant damping, and detailed studies are in preparation that demonstrates the requirements necessary to adapt such a support system to survive launch loads (photo taken at RFCML by E.S.D.).

## 5. CONCLUSION

This manuscript provides a brief introduction to the development of space telescopes, a sampling of technologies that have enabled new concepts such as continuous wavefront control and correction of large borosilicate mirrors at lower costs, and introduces pieces of an observatory concept that seeks to learn from successful Small-Sats, ground-based observatories, as well as investments in flagship observatory technology maturation. Other manuscripts in these proceedings present additional related concept studies. Future work will provide details of how such an observatory might come about, additional risk mitigation strategies, detailed instrument designs, and present the environmental requirements necessary for a honey-comb borosilicate mirror to survive launch.

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## REFERENCES

- [1] Roman, N. G., “LST: The National Space Observatory concept - An observatory for future astronomer involvement in planning and use,” in [NTRS Meeting Information: Aerospace Sciences Meeting; 1974-01-30 to 1974-02-01], NTRS Document ID: 19740056405, Washington, D.C. (Jan. 1974).
- [2] Linsky, J. L., “UV astronomy throughout the ages: a historical perspective,” *Astrophys Space Sci* **363**, 101 (Apr. 2018).
- [3] Rieke, G. H., [*The Last of the Great Observatories: Spitzer and the Era of Faster, Better, Cheaper at NASA*], University of Arizona Press (Nov. 2021).

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<sup>§</sup><https://www.ssl.berkeley.edu/ssl-mourns-the-passing-of-dr-michael-logan-lampton-1941-2023/>

- [4] Smith, L., Lucas, F. D., Rohrabacher, D., Brooks, M., Hultgren, R., Posey, B., Massie, T., Weber, R. K., Knight, S., Babin, B., Comstock, B., Loudermilk, B., Abraham, R. L., Palmer, G., Webster, D., Banks, J., Biggs, A., Marshall, R. W., Dunn, N. P., Higgins, C., Norman, R., Carolina, S., Lesko, D., Johnson, E. B., Lofgren, Z., Lipinski, D., Bonamici, S., Bera, A., Esty, E. H., Veasey, M. A., Beyer, D. S., Rosen, J., Lamb, C., and Babin, H. B., "NASA cost and schedule overruns: acquisition and program management challenges," (June 2018).
- [5] Quintana, E. V., Colón, K. D., Mosby, G., Schlieder, J. E., Supsinskas, P., Karburn, J., Dotson, J. L., Greene, T. P., Hedges, C., Apai, D., Barclay, T., Christiansen, J. L., Espinoza, N., Mullally, S. E., Gilbert, E. A., Hoffman, K., Kostov, V. B., Lewis, N. K., Foote, T. O., Mason, J., Youngblood, A., Morris, B. M., Newton, E. R., Pepper, J., Rackham, B. V., Rowe, J. F., and Stevenson, K., "The Pandora SmallSat: Multiwavelength Characterization of Exoplanets and their Host Stars," (Aug. 2021).
- [6] van Belle, G. T., Meinel, A. B., and Meinel, M. P., "The scaling relationship between telescope cost and aperture size for very large telescopes," in [*Ground-based Telescopes*], Oschmann, Jacobus M., J., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5489**, 563–570 (Oct. 2004).
- [7] Witze, A., "The \$11-billion Webb telescope aims to probe the early Universe," *Nature* **600**, 208–212 (Dec. 2021).
- [8] Ballhaus, W. F., Casani, J., Dorman, S., Gallagher, D., Illingworth, G., Klineberg, J., Schurr, D., Lewis, R., and Lobbia, M., "James webb space telescope independent comprehensive review panel final report," tech. rep., JWST-ICRP (2010).
- [9] Elvis, M., Lawrence, C., and Seager, S., "Accelerating astrophysics with the SpaceX Starship," *Physics Today* **76**, 40–45 (Feb. 2023).
- [10] Angel, J. R. P. and Hill, J. M., "Manufacture Of Large Glass Honeycomb Mirrors," in [*Advanced Technology Optical Telescopes I*], **0332**, 298–306, SPIE (Nov. 1982).
- [11] Nelson, J. E. and Mast, T. S., "Construction of the Keck Observatory," in [*Proceedings of a ESO Conference on Very Large Telescopes and their Instrumentation*], **30**, 7 (Oct. 1988).
- [12] Martin, G., "NewSpace: The Emerging Commercial Space Industry," in [*ISU Master Class Lecture*], (Feb. 2017).
- [13] Rizk, B., Drouet d'Aubigny, C., Golish, D., Fellows, C., Merrill, C., Smith, P., Walker, M. S., Hendershot, J. E., Hancock, J., Bailey, S. H., DellaGiustina, D. N., Lauretta, D. S., Tanner, R., Williams, M., Harshman, K., Fitzgibbon, M., Verts, W., Chen, J., Connors, T., Hamara, D., Dowd, A., Lowman, A., Dubin, M., Burt, R., Whiteley, M., Watson, M., McMahon, T., Ward, M., Booher, D., Read, M., Williams, B., Hunten, M., Little, E., Saltzman, T., Alfred, D., O'Dougherty, S., Walthall, M., Kenagy, K., Peterson, S., Crowther, B., Perry, M. L., See, C., Selznick, S., Sauve, C., Beiser, M., Black, W., Pfisterer, R. N., Lancaster, A., Oliver, S., Oquest, C., Crowley, D., Morgan, C., Castle, C., Dominguez, R., and Sullivan, M., "OCAMS: The OSIRIS-REx Camera Suite," *Space Sci Rev* **214**, 26 (Jan. 2018).
- [14] Chung, H., Vargas, C. J., Hamden, E., McMahon, T., Gonzales, K., Khan, A. R., Agarwal, S., Bailey, H., Behroozi, P., Brendel, T., Choi, H., Connors, T., Corlies, L., Corliss, J., Dettmar, R.-J., Dolana, D., Douglas, E. S., Guzman, J., Hamara, D., Harris, W., Harshman, K., Hergenrother, C., Hoadley, K., Kidd, J., Kim, D., Li, J. S., Montoya, M., Sauve, C., Schiminovich, D., Selznick, S., Siegmund, O., Ward, M., Wolcott, E. M., and Zaritsky, D., "Aspera: the UV SmallSat telescope to detect and map the warm-hot gas phase in nearby galaxy halos," in [*UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts X*], **11819**, 1181903, International Society for Optics and Photonics (Aug. 2021).
- [15] Spitzer, L., "Space telescopes and components," *The Astronomical Journal* **65**, 242 (June 1960).
- [16] SPITZER, LYMAN., "THE BEGINNINGS AND FUTURE OF SPACE ASTRONOMY," *American Scientist* **50**(3), 473–484 (1962).
- [17] Roman, N. G. and DeVorkin, D., "AIP ORAL HISTORIES Nancy G. Roman," (Aug. 1980).
- [18] Hammond, A. L., "Ultraviolet Astronomy: Progress with the OAO," *Science* **170**, 960–961 (Nov. 1970).
- [19] Shockley, E. F., "A study of the longevity and operational reliability of Goddard Spacecraft, 1960-1980," Tech. Rep. NASA-TM-82178 (Aug. 1981).

- [20] Aumann, H. H. and Walker, R. G., "Infrared Astronomical Satellite," *Opt. Eng.* **16**(6), 166537–166537–(1977).
- [21] Boggess, A., Carr, F. A., Evans, D. C., Fischel, D., Freeman, H. R., Fuechsel, C. F., Klinglesmith, D. A., Krueger, V. L., Longanecker, G. W., Moore, J. V., Pyle, E. J., Rebar, F., Sizemore, K. O., Sparks, W., Underhill, A. B., Vitagliano, H. D., West, D. K., Macchietto, F., Fitton, B., Barker, P. J., Dunford, E., Gondhalekar, P. M., Hall, J. E., Harrison, V. a. W., Oliver, M. B., Sandford, M. C. W., Vaughan, P. A., Ward, A. K., Anderson, B. E., Boksenberg, A., Coleman, C. I., Snijders, M. a. J., and Wilson, R., "The IUE spacecraft and instrumentation," *Nature* **275**, 372–377 (Oct. 1978).
- [22] Meinel, A. B., [High Resolution Optical Space Telescopes] (Jan. 1962).
- [23] Meinel, A. B., "New Frontiers of Astronomical Technology: Technological developments challenge the astronomer, both from the ground and in space..," *Science* **134**, 1165–1171 (Oct. 1961).
- [24] Richard, R. M., Cho, M., and Pollard, W., "Dynamic Analysis Of The SIRTF One-Meter Mirror During Launch," in [*Cryogenic Optical Systems and Instruments III*], **0973**, 86–99, SPIE (Apr. 1988).
- [25] Baiocchi, D., Burge, J. H., and Cuerden, B., "Demonstration of a 0.5-m ultralightweight mirror for use at geosynchronous orbit," in [*Optical Manufacturing and Testing IV*], **4451**, 86–95, SPIE (Dec. 2001).
- [26] Baiocchi, D., *Design and control of lightweight, active space mirrors*, PhD thesis (Dec. 2004).
- [27] Baiocchi, D. and Burge, J. H., "Optimized active lightweight space mirrors," in [*UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts*], **5166**, 49–57, SPIE (Jan. 2004).
- [28] Cohan, L. E. and Miller, D. W., "Vibroacoustic launch analysis and alleviation of lightweight, active mirrors," *OE* **50**, 013002 (Jan. 2011).
- [29] Saif, B., Chaney, D., Smith, W. S., Greenfield, P., Hack, W., Bluth, J., Otten, A. V., Bluth, M., Sanders, J., Keski-Kuha, R., Feinberg, L., North-Morris, M., and Millerd, J., "Nanometer level characterization of the James Webb Space Telescope optomechanical systems using high-speed interferometry," *Appl. Opt., AO* **54**, 4285–4298 (May 2015).
- [30] Briguglio, R., Xompero, M., Riccardi, A., Lisi, F., Duò, F., Vettore, C., Gallieni, D., Tintori, M., Lazzarini, P., Patauner, C., Biasi, R., D'Amato, F., Pucci, M., and do Carmo, J. P., "Development of large aperture telescope technology (LATT): test results on a demonstrator bread-board," in [*International Conference on Space Optics — ICSO 2014*], **10563**, 1275–1283, SPIE (Nov. 2017).
- [31] Junkins, J. L., Rahman, Z. H., and Bang, H., "Near-minimum-time control of distributed parameter systems - Analytical and experimental results," *Journal of Guidance, Control, and Dynamics* **14**, 406–415 (Mar. 1991).
- [32] Saenz-Otero, A. and Miller, D. W., "Using ISS to develop telescope technology," in [*UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts II*], **5899**, 172–183, SPIE (Aug. 2005).
- [33] Crawley, E. F., Vanschoor, M. C., and Bokhour, E. B., "The middeck 0-gravity dynamics experiment," Tech. Rep. NASA-CR-4500 (Jan. 1993).
- [34] Miller, D., de Luis, J., Stover, G., How, J., Liu, K., Grocott, S., Campbell, M., Glaese, R., and Crawley, E., "The Middeck Active Control Experiment (MACE): using space for technology research and development," in [*Proceedings of 1995 American Control Conference - ACC'95*], **1**, 397–401 vol.1 (June 1995).
- [35] Brooks, T., Stahl, H. P., and Sr, W. R. A., "Advanced Mirror Technology Development (AMTD) thermal trade studies," in [*Optical Modeling and Performance Predictions VII*], **9577**, 957703, SPIE (Sept. 2015).
- [36] Brooks, T. E. and Stahl, H. P., "Precision thermal control technology to enable thermally stable telescopes," *JATIS* **8**, 024001 (Apr. 2022).
- [37] Stahl, H. P., Feinberg, L. D., and Texter, S. C., "JWST primary mirror material selection," in [*Proc. SPIE*], **5487**, 818–825, International Society for Optics and Photonics (Oct. 2004).
- [38] Stahl, H. P., "JWST mirror technology development results," in [*Optical Manufacturing and Testing VII*], **6671**, 11–22, SPIE (Sept. 2007).
- [39] Matthews, G., Barrett, D., Bolton, J., Dahl, R., Michaels, E., Mallette, M., and Johnson, J., "Kodak AMSD mirror program: overview and cryo test results," in [*Optical Manufacturing and Testing V*], **5180**, 169–179, SPIE (Dec. 2003).
- [40] Catanzaro, B. and Doyle, D., "Herschel Space Telescope: Optical test and model correlation," in [*2009 IEEE Aerospace conference*], 1–14 (Mar. 2009).

- [41] West, S. C., Bailey, S. H., Bauman, S., Cuerden, B., Granger, Z., and Olbert, B. H., “A space imaging concept based on a 4m structured spun-cast borosilicate monolithic primary mirror,” in [*SPIE Astronomical Telescopes + Instrumentation*], Oschmann, Jr., J. M., Clampin, M. C., and MacEwen, H. A., eds., 77311O (July 2010).
- [42] Eads, R. W. and Angel, J. R. P., “A 20 m wide-field diffraction-limited telescope,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **379**, 20200141 (Nov. 2020).
- [43] Schneider, J., Silk, J., and Vakili, F., “OWL-Moon: Very high resolution spectropolarimetric interferometry and imaging from the Moon: exoplanets to cosmology,” *Exp Astron* (Aug. 2022).
- [44] Martin, S. R., Lawrence, C. R., Redding, D. C., Mennesson, B., Rodgers, J. M., Hurd, K., Morgan, R. M., Hu, R., Steeves, J. B., Jewell, J. B., Phillips, C., Pineda, C., Ferraro, N., and Flinois, T. L. B., “Next-generation active telescope for space astronomy,” *JATIS* **8**, 044005 (Dec. 2022).
- [45] Marlow, W. A., Carlton, A. K., Yoon, H., Clark, J. R., Haughwout, C. A., Cahoy, K. L., Males, J. R., Close, L. M., and Morzinski, K. M., “Laser-Guide-Star Satellite for Ground-Based Adaptive Optics Imaging of Geosynchronous Satellites,” *Journal of Spacecraft and Rockets* **54**(3), 621–639 (2017).
- [46] Douglas, E. S., Males, J. R., Clark, J., Guyon, O., Lumbres, J., Marlow, W., and Cahoy, K. L., “Laser Guide Star for Large Segmented-aperture Space Telescopes. I. Implications for Terrestrial Exoplanet Detection and Observatory Stability,” *AJ* **157**, 36 (Jan. 2019).
- [47] Pogorelyuk, L., Serra, P., Kacker, S., Vlahakis, S., Belsten, N., Rau, G., Carpenter, K. G., Pueyo, L., Monnier, J. D., Douglas, E. S., and Cahoy, K. L., “Laser-guided space interferometer,” in [*Optical and Infrared Interferometry and Imaging VIII*], **12183**, 508–521, SPIE (Aug. 2022).
- [48] Gersh-Range, J. and Perrin, M. D., “Improving active space telescope wavefront control using predictive thermal modeling,” *J. Astron. Telesc. Instrum. Syst.* **1**(1), 014004 (2015).
- [49] Mendillo, C. B., Chakrabarti, S., Cook, T. A., Hicks, B. A., and Lane, B. F., “Flight demonstration of a milliarcsecond pointing system for direct exoplanet imaging,” *Appl. Opt.* **51**, 7069–7079 (Oct. 2012).
- [50] Douglas, E. S., Mendillo, C. B., Cook, T. A., Cahoy, K. L., and Chakrabarti, S., “Wavefront sensing in space: flight demonstration II of the PICTURE sounding rocket payload,” *Journal of Astronomical Telescopes, Instruments, and Systems* **4**, 019003 (Jan. 2018).
- [51] Cahoy, K. L., Marinan, A. D., Novak, B., Kerr, C., Nguyen, T., Webber, M., Falkenburg, G., and Barg, A., “Wavefront control in space with MEMS deformable mirrors for exoplanet direct imaging,” *J. Micro/Nanolith. MEMS MOEMS* **13**(1), 011105–011105 (2013).
- [52] Douglas, E., Allan, G., Morgan, R., Holden, B. G., Gubner, J., Haughwout, C., do Vale Pereira, P., Xin, Y., Merk, J., and Cahoy, K. L., “Small Mirrors for Small Satellites: Design of the Deformable Mirror Demonstration Mission CubeSat (DeMi) Payload,” *Front. Astron. Space Sci.* **0** (2021).
- [53] Morgan, R. E., Vlahakis, S., Douglas, E., Allan, G., Pereira, P. d. V., Egan, M., Furesz, G., Gubner, J., Haughwout, C., Holden, B., Merk, J., Murphy, T., Pogorelyuk, L., Roascio, D., Xin, Y., and Cahoy, K., “On-orbit operations summary for the Deformable Mirror Demonstration Mission (DeMi) CubeSat,” in [*Adaptive Optics Systems VIII*], **12185**, 2423–2432, SPIE (Aug. 2022).
- [54] Perrin, M. D., Soummer, R., Elliott, E. M., Lallo, M. D., and Sivaramakrishnan, A., “Simulating point spread functions for the James Webb Space Telescope with WebbPSF,” in [*Proc. SPIE*], **8442**, 84423D–84423D–11 (2012).
- [55] Greenbaum, A. Z. and Sivaramakrishnan, A., “In-focus wavefront sensing using non-redundant mask-induced pupil diversity,” *Opt. Express*, *OE* **24**, 15506–15521 (July 2016).
- [56] Mennesson, B., Bailey, V. P., Zellem, R., Hildebrandt, S., Ygouf, M., Rhodes, J., Zimmerman, N., Nemati, B., Gonzalez, G., Cady, E., Kern, B., Koch, T., Krist, J., Heydorff, K., Luchik, T., Mok, F., Morrissey, P., Poberezhskiy, I., Riggs, A. J., Shi, F., Zhao, F., Akeson, R., Armus, L., Greenbaum, A., Ingalls, J., and Lowrance, P., “The Roman Space Telescope coronagraph technology demonstration: current status and relevance to future missions,” in [*Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*], **12180**, 685–697, SPIE (Aug. 2022).

- [57] Poberezhskiy, I., Luchik, T., Zhao, F., Frerking, M., Basinger, S., Cady, E., Colavita, M. M., Creager, B., Fathpour, N., Goullioud, R., Groff, T., Morrissey, P., Kempenaar, J., Kern, B., Koch, T., Krist, J., Mok, F., Muliere, D., Nemati, B., Riggs, A. J., Seo, B.-J., Shi, F., Shreckengost, B., Steeves, J., and Tang, H., “Roman space telescope coronagraph: engineering design and operating concept,” in [*Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave*], **11443**, 114431V, International Society for Optics and Photonics (Jan. 2021).
- [58] Krist, J., “CGISim (Roman coronagraph) Simulator: Public version (uses synthetic instead of measured primary & secondary optic error maps), V3.1.” <https://sourceforge.net/projects/cgisim/> (2022).
- [59] Gersh-Range, J., Riggs, A. J., and Kasdin, N. J., “Flight designs and pupil error mitigation for the bowtie shaped pupil coronagraph on the Nancy Grace Roman Space Telescope,” *J. Astron. Telesc. Instrum. Syst.* **8**(2), 025003 (2022).
- [60] Gersh-Range, J., “Publicly available tools and the overall process for generating Observing Scenario (OS) 11 polarization datasets for the wide-field-of-view shaped pupil coronagraph.” [https://roman.ipac.caltech.edu/docs/Tools\\_and\\_Process.pdf](https://roman.ipac.caltech.edu/docs/Tools_and_Process.pdf) (2022).
- [61] Dean, B. H., Aronstein, D. L., Smith, J. S., Shiri, R., and Acton, D. S., “Phase retrieval algorithm for JWST Flight and Testbed Telescope,” in [*Space Telescopes and Instrumentation I: Optical, Infrared, and Millimeter*], **6265**, 314–330, SPIE (June 2006).
- [62] Perrin, M. D., Soummer, R., Choquet, É., N'Diaye, M., Levecq, O., Lajoie, C.-P., Ygouf, M., Leboulleux, L., Egron, S., Anderson, R., Long, C., Elliott, E., Hartig, G., Pueyo, L., van der Marel, R., and Mountain, M., “James Webb Space Telescope Optical Simulation Testbed I: Overview and First Results,” *arXiv:1407.0591 [astro-ph]* , 914309 (Aug. 2014).
- [63] Lajoie, C.-P., Lallo, M., Meléndez, M., Flagey, N., Telfer, R., Comeau, T. M., Kulp, B. A., Beck, T., Brady, G. R., and Perrin, M. D., “A Year of Wavefront Sensing with JWST in Flight: Cycle 1 Telescope Monitoring and Maintenance Summary,” (July 2023).
- [64] Williams, I., Dahlgren, M., Roberts, T. G., and Karako, T., “Boost-Phase Missile Defense,” tech. rep., Center for Strategic and International Studies, Washington, D.C. (Fri, 06/24/2022 - 12:00).
- [65] Scoles, S., “Prime mover,” *Science* **377**, 702–705 (Aug. 2022).
- [66] Chang, K., “SpaceX Starship Test Launch: Highlights From SpaceX’s Scrubbed Starship Rocket Launch Attempt,” *The New York Times* (Apr. 2023).
- [67] Fossum, E. R., “The Invention of CMOS Image Sensors: A Camera in Every Pocket,” in [*2020 Pan Pacific Microelectronics Symposium (Pan Pacific)*], 1–6 (Feb. 2020).
- [68] Alarcon, M. R., Licandro, J., Serra-Ricart, M., Joven, E., Gaitan, V., and de Sousa, R., “Scientific CMOS Sensors in Astronomy: IMX455 and IMX411,” *PASP* **135**, 055001 (May 2023).
- [69] Goiffon, V., [*Radiation Effects on CMOS Active Pixel Image Sensors*], 295–332 (11 2015).
- [70] Leppinen, H., “Current use of linux in spacecraft flight software,” *IEEE Aerospace and Electronic Systems Magazine* **32**, 4–13 (Oct. 2017).
- [71] Canham, T., “The Mars Ingenuity Helicopter - A Victory for Open-Source Software,” in [*2022 IEEE Aerospace Conference (AERO)*], 01–11 (Mar. 2022).
- [72] Knapp, M., Seager, S., Demory, B.-O., Krishnamurthy, A., Smith, M. W., Pong, C. M., Bailey, V. P., Donner, A., Pasquale, P. D., Campuzano, B., Smith, C., Luu, J., Babuscia, A., Robert L. Bocchino, Jr., Loveland, J., Colley, C., Gedden, T., Kulkarni, T., Hughes, K., White, M., Krajewski, J., and Fesq, L., “Demonstrating High-precision Photometry with a CubeSat: ASTERIA Observations of 55 Cancri e,” *AJ* **160**, 23 (June 2020).
- [73] Smith, M., Donner, A., Knapp, M., Pong, C., Smith, C., Luu, J., Pasquale, P. D., and Campuzano, B., “On-Orbit Results and Lessons Learned from the ASTERIA Space Telescope Mission,” 20 (2018).
- [74] Ricker, G. R., Winn, J. N., Vanderspek, R., Latham, D. W., Bakos, G. Á., Bean, J. L., Berta-Thompson, Z. K., Brown, T. M., Buchhave, L., Butler, N. R., Butler, R. P., Chaplin, W. J., Charbonneau, D. B., Christensen-Dalsgaard, J., Clampin, M., Deming, D., Doty, J. P., Lee, N. D., Dressing, C., Dunham, E. W., Endl, M., Fressin, F., Ge, J., Henning, T., Holman, M. J., Howard, A. W., Ida, S., Jenkins, J. M., Jernigan, G., Johnson, J. A., Kaltenegger, L., Kawai, N., Kjeldsen, H., Laughlin, G., Levine, A. M., Lin, D., Lissauer, J. J., MacQueen, P., Marcy, G., McCullough, P. R., Morton, T. D., Narita, N., Paegert, M., Palle, E., Pepe,

- F., Pepper, J., Quirrenbach, A., Rinehart, S. A., Sasselov, D., Sato, B., Seager, S., Sozzetti, A., Stassun, K. G., Sullivan, P., Szentgyorgyi, A., Torres, G., Udry, S., and Villasenor, J., "Transiting Exoplanet Survey Satellite," *JATIS, JATIAG* **1**, 014003 (Oct. 2014).
- [75] Parker, J. J. K., Lebois, R. L., Lutz, S., Nickel, C., Ferrant, K., and Michaels, A., "Transiting Exoplanet Survey Satellite (TESS) flight dynamics commissioning results and experiences," *AAS GUIDANCE & CONTROL CONFERENCE* (2018).
- [76] Gangestad, J. W., Henning, G. A., Persinger, R. R., and Ricker, G. R., "A High Earth, Lunar Resonant Orbit for Lower Cost Space Science Missions," (Aug. 2013).
- [77] Hill, J., Martin, H., and Angel, R., "Honeycomb Mirrors for Large Telescopes," in [*Planets, Stars and Stellar Systems*], Oswalt, T. D. and McLean, I. S., eds., 137–184, Springer Netherlands, Dordrecht (2013).
- [78] Schlegel, D. J., Kollmeier, J. A., Aldering, G., Bailey, S., Baltay, C., Bebek, C., BenZvi, S., Besuner, R., Blanc, G., Bolton, A. S., Bouri, M., Brooks, D., Buckley-Geer, E., Cai, Z., Crane, J., Dey, A., Doel, P., Fan, X., Ferraro, S., Font-Ribera, A., Gutierrez, G., Guy, J., Heetderks, H., Huterer, D., Infante, L., Jelinsky, P., Johns, M., Karagiannis, D., Kent, S. M., Kim, A. G., Kneib, J.-P., Kronig, L., Konidaris, N., Lahav, O., Lampton, M. L., Lang, D., Leauthaud, A., Liguori, M., Linder, E. V., Magneville, C., Martini, P., Mateo, M., McDonald, P., Miller, C. J., Moustakas, J., Myers, A. D., Mulchaey, J., Newman, J. A., Nugent, P. E., Palanque-Delabrouille, N., Padmanabhan, N., Piro, A. L., Poppett, C., Prochaska, J. X., Pullen, A. R., Rabinowitz, D., Ramirez, S., Rix, H.-W., Ross, A. J., Samushia, L., Schaan, E., Schubnell, M., Seljak, U., Seo, H.-J., Shectman, S. A., Silber, J., Simon, J. D., Slepian, Z., Soares-Santos, M., Tarle, G., Thompson, I., Valluri, M., Wechsler, R. H., White, M., Wilson, M. J., Yeche, C., and Zaritsky, D., "Astro2020 APC White Paper: The MegaMapper: a  $z > 2$  spectroscopic instrument for the study of Inflation and Dark Energy," (July 2019).
- [79] Korsch, D., "Anastigmatic three-mirror telescope," *Appl. Opt.*, **AO** **16**, 2074–2077 (Aug. 1977).
- [80] Feinberg, L. D., Dean, B. H., Hayden, W. L., Howard, J. M., Keski-Kuha, R. A., and Cohen, L. M., "Space telescope design considerations," *OE* **51**, 011006 (Feb. 2012).
- [81] Roddier, C. and Roddier, F., "Combined approach to the Hubble Space Telescope wave-front distortion analysis," *Applied optics* **32**(16), 2992–3008 (1993).
- [82] Litvak, M. M., "Image inversion analysis of the HST OTA (Hubble Space Telescope Optical Telescope Assembly), phase A," Tech. Rep. JPL-9950-1381 (July 1991).
- [83] Krist, J. E. and Burrows, C. J., "Phase-retrieval analysis of pre- and post-repair Hubble Space Telescope images," *Applied Optics* **34**, 4951 (Aug. 1995).
- [84] Schlawin, E., Beatty, T., Brooks, B., Nikolov, N. K., Greene, T. P., Espinoza, N., Glidic, K., Baka, K., Egami, E., Stansberry, J., Boyer, M., Gennaro, M., Leisenring, J., Hilbert, B., Misselt, K., Kelly, D., Canipe, A., Beichman, C., Correnti, M., Knight, J. S., Jurling, A., Perrin, M. D., Feinberg, L. D., McElwain, M. W., Bond, N., Ciardi, D., Kendrew, S., and Rieke, M., "JWST NIRCam Defocused Imaging: Photometric Stability Performance and How It Can Sense Mirror Tilts," *PASP* **135**, 018001 (Jan. 2023).
- [85] Nguyen, T., Morgan, E., Vanderspek, R., Levine, A., Kephart, M., Francis, J., Zapetis, J., Cahoy, K., and Jr, G. R., "Fine-pointing performance and corresponding photometric precision of the Transiting Exoplanet Survey Satellite," *JATIS* **4**, 047001 (Sept. 2018).
- [86] Bartusek, L. M., Davis, J. L., and Vess, M. F., "Nancy Grace Roman Space Telescope Observatory Implementation and Challenges," in [*2022 IEEE Aerospace Conference (AERO)*], 01–14 (Mar. 2022).
- [87] Parnin, C., Helms, E., Atlee, C., Boughton, H., Ghattas, M., Glover, A., Holman, J., Micco, J., Murphy, B., Savor, T., Stumm, M., Whitaker, S., and Williams, L., "The Top 10 Adages in Continuous Deployment," *IEEE Software* **34**, 86–95 (May 2017).
- [88] Tibazarwa, A., "Strategic Integration for Hardware and Software Convergence Complexity," *IEEE Engineering Management Review* **49**(3), 92–102 (2021).
- [89] O'Mullane, W., Economou, F., Lim, K.-T., Mueller, F., Jenness, T., Dubois-Felsmann, G. P., Guy, L. P., Sullivan, I. S., AlSayyad, Y., Swinbank, J. D., and Krughoff, K. S., "Software architecture and system design of rubin observatory," (2022).
- [90] Holm, J., "Making Sense of Rocket Science - Building NASA's Knowledge Management Program," in [*Hawaii International Conference on System Sciences*], (Jan. 2002).

- [91] Douglas, E. S., Carlton, A. K., Cahoy, K. L., Kasdin, N. J., Turnbull, M., and Macintosh, B., “WFIRST coronagraph technology requirements: status update and systems engineering approach,” in [*Modeling, Systems Engineering, and Project Management for Astronomy VIII*], **10705**, 1070526, International Society for Optics and Photonics (July 2018).
- [92] Browning, J. and Adams, R., “Doorstop: Text-Based Requirements Management Using Version Control,” *Journal of Software Engineering and Applications* **07**(03), 187–194 (2014).
- [93] Olbert, B. H., Angel, J. R. P., Hill, J. M., and Hinman, S. F., “Casting 6.5-meter mirrors for the MMT conversion and Magellan,” in [*Advanced Technology Optical Telescopes V*], **2199**, 144–155, SPIE (June 1994).
- [94] Martin, H. M., Burge, J. H., Ketelsen, D. A., and West, S. C., “Fabrication of the 6.5-m primary mirror for the Multiple Mirror Telescope Conversion,” in [*Optical Telescopes of Today and Tomorrow*], Ardeberg, A. L., ed., 399–404 (Mar. 1997).
- [95] Martin, H. M., Allen, R. G., Burge, J. H., Dettmann, L. R., Ketelsen, D. A., Kittrell, W. C., and Miller, S. M., “Polishing of a 6.5-m f/1.25 mirror for the first Magellan telescope,” in [*Optical Systems Design and Production*], Geyl, R. and Maxwell, J., eds., 47 (Sept. 1999).
- [96] Kingsley, J. S., Angel, R., Davison, W., Neff, D., Teran, J., Assenmacher, B., Peyton, K., Martin, H. M., Oh, C., Kim, D., Pearce, E., Rascon, M., Connors, T., Alfred, D., Jannuzzi, B. T., Zaritsky, D., Christensen, E., Males, J., Hinz, P., Seaman, R., Gonzales, K., and Adriaanse, D., “An inexpensive turnkey 6.5m observatory with customizing options,” in [*Ground-based and Airborne Telescopes VII*], **10700**, 107004H, International Society for Optics and Photonics (July 2018).
- [97] Miyata, T., Yoshii, Y., Doi, M., Kohno, K., Tanaka, M., Motohara, K., Minezaki, T., Sako, S., Morokuma, T., Tanabe, T., Hatsukade, B., Konishi, M., Takahashi, H., Kamizuka, T., Egusa, F., Sameshima, H., Asano, K., Nishimura, A., Koyama, S., Kato, N., Numata, M., Aoki, T., Bronfman, L., Ruiz, M., Hamuy, M., Mendez, R., Garay, G., and Escala, A., “The University of Tokyo Atacama Observatory 6.5m telescope: project status 2022,” in [*Ground-based and Airborne Telescopes IX*], **12182**, 385–393, SPIE (Aug. 2022).
- [98] Kim, D. and et al, “Compact Three Mirror Anastigmat Space Telescope Design using 6.5m Monolithic Primary Mirror,” in [*Proc SPIE*], **12677** (2023).
- [99] Choi, H. and et al, “Approaches to developing tolerance and error budget for active three mirror anastigmat space telescopes,” in [*Proc SPIE*], **12677** (2023).
- [100] Derby, K. Z. and et al, “Integrated modeling of wavefront sensing and control for space telescopes utilizing active and adaptive optics,” in [*Proc SPIE*], **12677** (2023).
- [101] Kang, H. and et al, “Focus diverse phase retrieval testbed development of continuous wavefront sensing for space telescope applications,” in [*Proc SPIE*], **12677** (2023).
- [102] Blomquist, S. and et al, “Analysis of Active Optics Correction for a 6.5m Honeycomb Mirror in a Space Observatory,” in [*Proc SPIE*], **12677** (2023).
- [103] Nurre, G. S., Anhouse, S. J., and Gullapalli, S. N., “Hubble Space Telescope Fine Guidance Sensor Control System,” in [*Acquisition, Tracking, and Pointing III*], **1111**, 327–343, International Society for Optics and Photonics (Sept. 1989).
- [104] Bahcall, J. N. and Soneira, R. M., “The universe at faint magnitudes. I-Models for the galaxy and the predicted star counts,” *The Astrophysical Journal Supplement Series* **44**, 73–110 (1980).
- [105] Elliott, A., Richardson, N. D., Pablo, H., Moffat, A. F. J., Bowman, D. M., Ibrahim, N., Handler, G., Lovekin, C., Popowicz, A., St-Louis, N., Wade, G. A., and Zwintz, K., “5 yr of BRITE-Constellation photometry of the luminous blue variable P Cygni: properties of the stochastic low-frequency variability,” *Monthly Notices of the Royal Astronomical Society* **509**, 4246–4255 (Jan. 2021).
- [106] Perlmutter, S., Aldering, G., Baltay, C., Deustua, S., Freedman, W., Fruchter, A., Rubin, D., Sako, M., and Suntzeff, N., “The Key Role of Supernova Spectrophotometry in the Next-Decade Dark Energy Science Program,” *Bulletin of the American Astronomical Society* **51**, 494 (May 2019).
- [107] Boone, K., Aldering, G., Antilogus, P., Aragon, C., Bailey, S., Baltay, C., Bongard, S., Buton, C., Copin, Y., Dixon, S., Fouchez, D., Gangler, E., Gupta, R., Hayden, B., Hillebrandt, W., Kim, A. G., Kowalski, M., Küsters, D., Léget, P. F., Mondon, F., Nordin, J., Pain, R., Pecontal, E., Pereira, R., Perlmutter, S., Ponder, K. A., Rabinowitz, D., Rigault, M., Rubin, D., Runge, K., Saunders, C., Smadja, G., Suzuki,

- N., Tao, C., Taubenberger, S., Thomas, R. C., and Vincenzi, M., "The Twins Embedding of Type Ia Supernovae. I. The Diversity of Spectra at Maximum Light," *ApJ* **912**, 70 (May 2021).
- [108] Boone, K., Aldering, G., Antilogus, P., Aragon, C., Bailey, S., Baltay, C., Bongard, S., Buton, C., Copin, Y., Dixon, S., Fouchez, D., Gangler, E., Gupta, R., Hayden, B., Hillebrandt, W., Kim, A. G., Kowalski, M., Küsters, D., Léget, P. F., Mondron, F., Nordin, J., Pain, R., Pecontal, E., Pereira, R., Perlmutter, S., Ponder, K. A., Rabinowitz, D., Rigault, M., Rubin, D., Runge, K., Saunders, C., Smadja, G., Suzuki, N., Tao, C., Taubenberger, S., Thomas, R. C., and Vincenzi, M., "The Twins Embedding of Type Ia Supernovae. II. Improving Cosmological Distance Estimates," *ApJ* **912**, 71 (May 2021).
- [109] Peters-Limbach, M. A., Groff, T. D., Kasdin, N. J., Driscoll, D., Galvin, M., Foster, A., Carr, M. A., LeClerc, D., Fagan, R., McElwain, M. W., Knapp, G., Brandt, T., Janson, M., Guyon, O., Jovanovic, N., Martinache, F., Hayashi, M., and Takato, N., "The optical design of CHARIS: an exoplanet IFS for the Subaru telescope," in [*Proc. SPIE*], **8864**, 88641N–88641N–15 (2013).
- [110] Claudi, R. U., Turatto, M., Giro, E., Mesa, D., Anselmi, U., Bruno, P., Cascone, E., De Caprio, V., Desidera, S., Dorn, R., Fantinel, D., Finger, G., Gratton, R. G., Lessio, L., Lizon, J. L., Salasnic, B., Scuderi, S., Dohlen, Kj., Beuzit, J. L., Puget, P., Antichi, J., Hubin, N., and Kasper, M., "SPHERE IFS: the spectro differential imager of the VLT for exoplanets search," **7735**, 77350V–77350V–11 (2010).
- [111] Lantz, B., Aldering, G., Antilogus, P., Bonnaud, C., Capoani, L., Castera, A., Copin, Y., Dubet, D., Gangler, E., Henault, F., Lemonnier, J.-P., Pain, R., Pecontal, A., Pecontal, E., and Smadja, G., "SNIFS: a wideband integral field spectrograph with microlens arrays," in [*Optical Design and Engineering*], Mazuray, L., Rogers, P. J., and Wartmann, R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5249**, 146–155 (Feb. 2004).
- [112] Bacon, e. a., "The MUSE second-generation VLT instrument," in [*Ground-based and Airborne Instrumentation for Astronomy III*], McLean, I. S., Ramsay, S. K., and Takami, H., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7735**, 773508 (July 2010).
- [113] Prieto, E., Ealet, A., Milliard, B., Aumeunier, M.-H., Bonissent, A., Cerna, C., Crouzet, P.-E., Karst, P., Kneib, J.-P., Malina, R., Pamplona, T., Rossin, C., Smadja, G., and Vives, S., "An integral field spectrograph for SNAP," in [*Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter*], Oschmann, Jacobus M., J., de Graauw, M. W. M., and MacEwen, H. A., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7010**, 701019 (July 2008).
- [114] Gao, G., Pasquale, B. A., Marx, C. T., and Chambers, V. J., "Optical design of theWFIRST Phase-A Integral Field Channel," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Clark, P. P., Muschawec, J. A., Pfisterer, R. N., and Rogers, J. R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10590**, 105901R (Nov. 2017).
- [115] Mendillo, C. B., Hewawasam, K., Howe, G. A., Martel, J., Cook, T. A., and Chakrabarti, S., "The PICTURE-C exoplanetary direct imaging balloon mission: first flight preparation," in [*Techniques and Instrumentation for Detection of Exoplanets IX*], **11117**, 101–111, SPIE (Sept. 2019).
- [116] Maier, E. R., Douglas, E. S., Kim, D. W., Su, K., Ashcraft, J. N., Breckinridge, J. B., Choi, H., Choquet, E., Connors, T. E., Durney, O., Gonzales, K. L., Guthery, C. E., Haughwout, C. A., Heath, J. C., Hyatt, J., Lumbres, J., Males, J. R., Matthews, E. C., Milani, K., Montoya, O. M., N'Diaye, M., Noenickx, J., Pogorelyuk, L., Ruane, G., Schneider, G., Smith, G. A., and Stark, C. C., "Design of the vacuum high contrast imaging testbed for CDEEP, the Coronagraphic Debris and Exoplanet Exploring Pioneer," in [*Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave*], **11443**, 114431Y, International Society for Optics and Photonics (Dec. 2020).
- [117] Ashcraft, J. N., Choi, H., Douglas, E. S., Derby, K., Van Gorkom, K., Kim, D., Anche, R., Carter, A., Durney, O., Haffert, S., Harrison, L., Kautz, M., Lumbres, J., Males, J. R., Milani, K., Montoya, O. M., and Smith, G. A., "The Space Coronagraph Optical Bench (SCoOB): 1. Design and Assembly of a Vacuum-compatible Coronagraph Testbed for Spaceborne High-Contrast Imaging Technology," (Aug. 2022).
- [118] Van Gorkom, K., Douglas, E. S., Ashcraft, J. N., Haffert, S., Kim, D., Choi, H., Anche, R. M., Males, J. R., Milani, K., Derby, K., Harrison, L., and Durney, O., "The space coronagraph optical bench (SCoOB): 2. wavefront sensing and control in a vacuum-compatible coronagraph testbed for spaceborne high-contrast imaging technology," (Aug. 2022).

- [119] Blaurock, C., McGinnis, M., Kim, K., and Mosier, G. E., “Structural-thermal-optical performance (STOP) sensitivity analysis for the James Webb Space Telescope,” in [*Optical Modeling and Performance Predictions II*], **5867**, 246–256, SPIE (Aug. 2005).
- [120] Saini, N., Anderson, K., Chang, Z., Gutt, G., and Nemati, B., “IMPipeline: an integrated STOP modeling pipeline for the WFIRST coronagraph (Conference Presentation),” in [*Techniques and Instrumentation for Detection of Exoplanets VIII*], **10400**, 1040008, International Society for Optics and Photonics (Oct. 2017).
- [121] Ashcraft, J. N., Douglas, E. S., Kim, D., Smith, G. A., Cahoy, K., Connors, T., Derby, K. Z., Gasho, V., Gonzales, K., Guthery, C. E., Kim, G. H., Sauve, C., and Serra, P., “The versatile CubeSat Telescope: going to large apertures in small spacecraft,” in [*UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts X*], **11819**, 1181904, International Society for Optics and Photonics (Aug. 2021).
- [122] Males, J. R. and Guyon, O., “Ground-based adaptive optics coronagraphic performance under closed-loop predictive control,” *JATIS, JATIAG* **4**, 019001 (Feb. 2018).
- [123] Lyon, R. G. and Clampin, M., “Space telescope sensitivity and controls for exoplanet imaging,” *OE, OPEGAR* **51**, 011002 (Feb. 2012).
- [124] Gersh-Range, J. and Perrin, M. D., “Improving active space telescope wavefront control using predictive thermal modeling,” *JATIS* **1**, 014004 (Oct. 2014).
- [125] Brooks, T., “Predictive thermal control applied to HabEx,” in [*UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VIII*], MacEwen, H. A. and Breckinridge, J. B., eds., 40, SPIE, San Diego, United States (Sept. 2017).
- [126] Males, J. R., Close, L. M., Miller, K., Schatz, L., Doelman, D., Lumbres, J., Snik, F., Rodack, A., Knight, J., Gorkom, K. V., Long, J. D., Hedglen, A., Kautz, M., Jovanovic, N., Morzinski, K., Guyon, O., Douglas, E., Follette, K. B., Lozi, J., Bohlman, C., Durney, O., Gasho, V., Hinz, P., Ireland, M., Jean, M., Keller, C., Kenworthy, M., Mazin, B., Noenickx, J., Alfred, D., Perez, K., Sanchez, A., Sauve, C., Weinberger, A., and Conrad, A., “MagAO-X: project status and first laboratory results,” in [*Adaptive Optics Systems VI*], **10703**, 1070309, International Society for Optics and Photonics (July 2018).
- [127] Guyon, O., Sevin, A., Gratadour, D., Bernard, J., Ltaief, H., Sukkari, D., Cetre, S., Skaf, N., Lozi, J., Martinache, F., Clergeon, C., Norris, B., Wong, A., and Males, J., “The compute and control for adaptive optics (CACAO) real-time control software package,” in [*Adaptive Optics Systems VI*], **10703**, 107031E, International Society for Optics and Photonics (July 2018).
- [128] Schatz, L., Codona, J., Long, J. D., Males, J. R., Pullen, W., Lumbres, J., Van Gorkom, K., Chambouleyron, V., Close, L. M., Correia, C., Fauvarque, O., Fusco, T., Guyon, O., Hart, M., Janin-Potiron, P., Johnson, R., Jovanovic, N., Mateen, M., Sauvage, J.-F., and Neichel, B., “Three-sided pyramid wavefront sensor. II. Preliminary demonstration on the new CACTI testbed,” (Oct. 2022).
- [129] Weckenborg, C., Kieckhäuser, K., Spengler, T. S., Bernstein, P., and Hahn, M., “Improving Resource Utilisation in Prototype Vehicle Production,” *Impact* **2020**, 13–18 (July 2020).
- [130] Swartwout, M., “CubeSat Mission Success (or Not): Trends and Recommendations,” (June 2015).
- [131] Clark, S., “Sweet success at last for Falcon 1 rocket,” (Sept. 2008).
- [132] Yost, B. D., Burkhard, C. D., Mayer, D. J., Weston, S. V., and Fishman, J. L., “Small Spacecraft Systems Virtual Institute’s Federated Databases and State of the Art of Small Spacecraft Report,” in [*Small Satellite Conference Proceedings*], SSC18-IV-06 (2018).
- [133] Bocchino, R., Canham, T., Watney, G., Reder, L., and Levison, J., “F Prime: An Open-Source Framework for Small-Scale Flight Software Systems,” *AIAA/USU Conference on Small Satellites* (Aug. 2018).
- [134] Tan, F., “2023 NASA Science: NASA SmallSats Missions for Science and Technology Demonstration,” (2023).
- [135] Martin, H. M., Ceragioli, R., Gasho, V., Jannuzzi, B. T., Kim, D. W., Kingsley, J. S., Law, K., Loeff, A., Lutz, R. D., Meyen, S., Oh, C. J., Tuell, M. T., Weinberger, S. N., West, S. C., Whitsitt, R., and Wortley, R., “Production of 8.4 m primary mirror segments for GMT,” in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V*], **12188**, 177–184, SPIE (Sept. 2022).

- [136] Martin, H. M., Callahan, S. P., Cuerden, B., Davison, W. B., DeRigne, S. T., Dettmann, L. R., Parodi, G., Trebisky, T. J., West, S. C., and Williams, J. T., “Active supports and force optimization for the MMT primary mirror,” in [*Astronomical Telescopes & Instrumentation*], Stepp, L. M., ed., 412–423 (Aug. 1998).
- [137] Martin, H. M., Angel, J. R. P., Burge, J. H., Cuerden, B., Davison, W. B., Johns, M., Kingsley, J. S., Kot, L. B., Lutz, R. D., Miller, S. M., Sheetman, S. A., Strittmatter, P. A., and Zhao, C., “Design and manufacture of 8.4m primary mirror segments and supports for the GMT,” in [*SPIE Astronomical Telescopes + Instrumentation*], Atad-Ettedgui, E., Antebi, J., and Lemke, D., eds., 62730E (June 2006).
- [138] Martin, H. M., Allen, R. G., Burge, J. H., Kim, D. W., Kingsley, J. S., Law, K., Lutz, R. D., Strittmatter, P. A., Su, P., Tuell, M. T., West, S. C., and Zhou, P., “Production of 8.4m segments for the Giant Magellan Telescope,” in [*Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II*], **8450**, 801–815, SPIE (Sept. 2012).
- [139] Martin, H. M., Ceragioli, R., Jannuzzi, B., Kim, D. W., Kingsley, J., Law, K., Loeff, A., Lutz, R., McMahon, T., Meyen, S., Oh, C. J., Tuell, M., Weinberger, S., West, S., and Wortley, R., “Manufacture of 8.4 m segments for the GMT primary mirror,” in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation IV*], Geyl, R. and Navarro, R., eds., 289, SPIE, Online Only, United States (Dec. 2020).
- [140] Pridgeon, A., “James B. Breckinridge (1939–2022),” *Bulletin of the AAS* **54** (Jan. 2022).